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Heating rates and mineral textures as indicators of fluid flow during metamorphism

B.L. DUTROW[1] , C.T. FOSTER, JR.[2], C.W. GABLE[3] AND B.J. TRAVIS[3]

[1] Dept. Geology & Geophysics, Louisiana St. Univ. Baton Rouge, LA, 70803,USA (dutrow@geol.lsu.edu)
[2] Dept. Geol., U. Iowa, Iowa City, IA (tomfoster@uiowa.edu)
[3] Los Alamos Ntl Lab, Los Alamos, NM (gable@lanl.gov; bjtravis@lanl.gov)

Fluid flow during metamorphism impacts the transport of heat as well as mass from a cooling intrusion. If permeability is sufficient for flow to occur, heat transported by the fluids significantly increases heating rates in the surrounding host rocks and is the dominant control on the spatial distribution of these high rates. The rate at which a particular temperature is crossed dictates the number of mineral nuclei that form and the scale of equilibration among minerals in the rock. In addition, passage of thermally heated fluids may result in multiple heating cycles thus increasing the cumulative time rocks spend at elevated temperature which influences mineral growth and equilibration. Alternatively, an apparent polymetamorphic mineral texture could develop. Heating rates associated with metamorphic thermal events as well as the cumulative time rocks spend in specific thermal zones are fundamental controls on the textural development of metamorphic rocks.

Three-dimensional computational modeling of heat and mass transport is used to track the passage of fluids through the crust during a contact metamorphic event. Calculations indicate that varying the depth (9-15km) and width (3-6km) of intrusion, geothermal gradient (28-36 $^oC/km$) and host rock permeabilities (10^{-15} to $10^{-18}m^2$) result in distinct patterns of high heating and elevated temperatures that track fluid advection. Visualization techniques designed for interpretation of these large datasets allow 4D mapping of dT/dt throughout the metamorphic event and permit analyses of the distribution of fast vs. slow heating rates, and hence nucleation as a function of space and time, and key controlling parameters. During a single metamorphic event accompanied by fluid convection, heating rates vary over four orders of magnitude at a single location, even with a constant permeability field. Consequently, models of mineral growth that use a constant heating rate are inadequate in these situations.

Our modeling studies suggest that the spatial and temporal distribution of variations in heating times and rates results in distinct patterns of crystal size and mineralogy and can be used to infer fluid advection in metamorphic environments.

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Hydrothermal apatite as a Sm-Nd geochronometer

J. SCHNEIDER, J. DOPIERALSKA AND U. HAACK

Institut für Geowissenschaften und Lithosphären-forschung, Senckenbergstraße 3, D-35390 Giessen (Jens.C.Schneider@geolo.uni-giessen.de)

Apatite is known to incorporate significant amounts of specific trace elements relevant for isotopic tracing and dating, making it suitable for combined U-Pb and (Rb)-Sr, but also for Lu-Hf [1] and Sm-Nd studies. Rare earth elements may amount to several percent in apatite, with the light REE having the highest partition coefficients [2].

Apatite rarely occurs in hydrothermal mineral deposits. Here we present Sm-Nd isotopic data for samples of hydrothermal apatite from abundant (apatite)-quartz-chlorite fissure veins in the SW Rhenish Massif, Germany, which belongs to the Rhenohercynian Zone of the central European Variscan orogenic belt. These veins are hosted by Lower Devonian shelf clastics and crosscut cleavage planes and thrust folds created by Variscan orogenic tectonics during the Upper Carboniferous. Therefore, their formation has been related to late-orogenic crustal extension and exhumation [3].

Eight analyzed apatites from these veins show overall high, but variable Sm and Nd elemental concentrations (Sm = 161-828 ppm, Nd = 245-561 ppm) and considerable spread in $^{147}Sm/^{144}Nd$ (0.356-0.909). Their $^{143}Nd/^{144}Nd$ ratios are radiogenic and range from 0.51247 to 0.51360. In a $^{143}Nd/^{144}Nd$ vs. $^{147}Sm/^{144}Nd$ diagram, they display a statistically robust regression line (MSWD = 1.12) corresponding to an isochron model age of 312.8 ± 2.4 Ma (Nd_i = 0.51174 ± 1, $\varepsilon_{Nd(t)}$ = -9.7) which we interpret as the formation age of (apatite)-quartz-chlorite fissure vein mineralization in the SW Rhenish Massif.

Our study shows that Sm-Nd geochronometry of apatite can be a powerful tool for directly dating hydrothermal mineralization. The age of 313 Ma predates the period of late-orogenic extension and exhumation in the Rhenohercynian realm (ca. 305-290 Ma) by at least 10 Ma. It places important constraints on the absolute timing of orogenic deformation in the Rhenohercynian crustal segment, demonstrating that the main phases of intense Variscan folding and thrusting must have occurred prior to ca. 313 Ma.

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